

CLFV and Neutrino Physics



*Cross frontier sessions RF-NF to discuss CLFV and neutrinos
Community Summer Study – Snowmass – Seattle, July 17–26, 2022*

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$$J = \frac{1}{2}$$

μ MASS (atomic mass units u)

The primary determination of a muon's mass comes from measuring the ratio of the mass to that of a nucleus, so that the result is obtained in u (atomic mass units). The conversion factor to MeV is more uncertain than the mass of the muon in u. In this datablock we give the result in u, and in the following datablock in MeV.

VALUE (u)	DOCUMENT ID	TECN	CHG	COMMENT
0.1134289264 ± 0.0000000030	MOHR	05	RVUE	2002 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.1134289168 ± 0.0000000034	¹ MOHR	99	RVUE	1998 CODATA value
0.113428913 ± 0.0000000017	² COHEN	87	RVUE	1986 CODATA value

¹ MOHR 99 make use of other 1998 CODATA entries below.

² COHEN 87 make use of other 1986 CODATA entries below.

μ MASS

2002 CODATA gives the conversion factor from u (atomic mass units, see the above datablock) as 931.494 043 (80). Earlier values use the then-current conversion factor. The conversion error dominates the masses given below.

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
105.6583692 ± 0.0000004	MOHR	05	RVUE	2002 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
105.6583568 ± 0.0000052	MOHR	99	RVUE	1998 CODATA v3
105.658353 ± 0.000016	³ COHEN	87	RVUE	1986 CODATA v3
105.658386 ± 0.000044	⁴ MARIAM	82	CNTR	+
105.65836 ± 0.00026	⁵ CROWE	72	CNTR	
105.65865 ± 0.00044	⁶ CRANE	71	CNTR	

³ Converted to MeV using the 1998 CODATA value of the conversion const: 931.494 013 ± 0.0000037 MeV/u.

⁴ MARIAM 82 give $m_\mu/m_e = 206.768259(62)$.

⁵ CROWE 72 give $m_\mu/m_e = 206.7682(5)$.

⁶ CRANE 71 give $m_\mu/m_e = 206.76878(85)$.

“Who Ordered That?”

The muon is the best known unstable fundamental particle.

The muon is also the heaviest fundamental particle we can directly work with. It is a unique, priceless resource for physicists.

ANS: “We did!”

μ MEAN LIFE τ

Measurements with an error $> 0.001 \times 10^{-6}$ s have been omitted.

VALUE (10^{-6} s)	DOCUMENT ID	TECN	CHG
2.19709 ± 0.00004 OUR AVERAGE			
2.197078 ± 0.000073	BARDIN	84	CNTR
2.197025 ± 0.000155	BARDIN	84	CNTR
2.19695 ± 0.00006	GIOVANETTI	84	CNTR
2.19711 ± 0.00008	BALANDIN	74	CNTR
2.1973 ± 0.0003	DUCLOS	73	CNTR

Piecing the Neutrino Mass Puzzle

Understanding the origin of neutrino masses and exploring the new physics in the lepton sector will require unique **theoretical** and **experimental** efforts ...

- understanding the fate of lepton-number. Neutrinoless double-beta decay.
- A comprehensive long baseline neutrino program.
- Probes of neutrino properties, including neutrino scattering experiments. And what are the neutrino masses anyway? Kinematical probes.
- **Precision measurements of charged-lepton properties ($g - 2$, edm) and searches for rare processes ($\mu \rightarrow e$ -conversion the best bet at the moment).**
- Collider experiments. The LHC and beyond may end up revealing the new physics behind small neutrino masses.
- Neutrino properties affect, in a significant way, the history of the universe. These can be “seen” in cosmic surveys of all types.
- Astrophysical Neutrinos – Supernovae and other Galaxy-shattering phenomena. Ultra-high energy neutrinos and correlations with not-neutrino messengers.

Charged-Lepton Flavor Violation

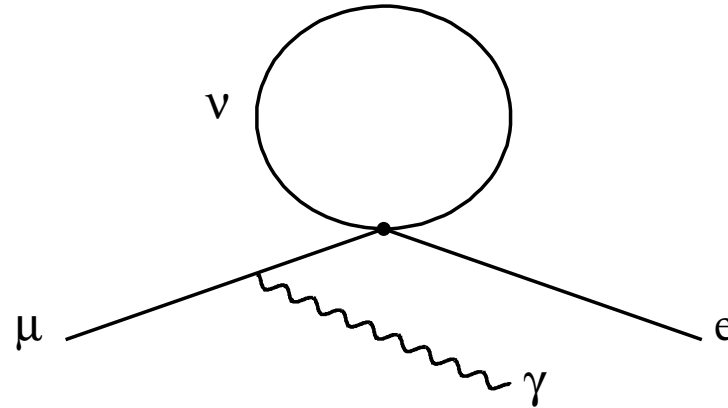
Concentrating on rare muon processes, like

$$\mu \rightarrow e\gamma$$

$$\mu \rightarrow ee^+e^-$$

$$\mu \rightarrow e\text{--conversion in nuclei}$$

Ever since it was established that $\mu \rightarrow e\nu\bar{\nu}$, people have searched for $\mu \rightarrow e\gamma$, which was thought to arise at one-loop, like this:



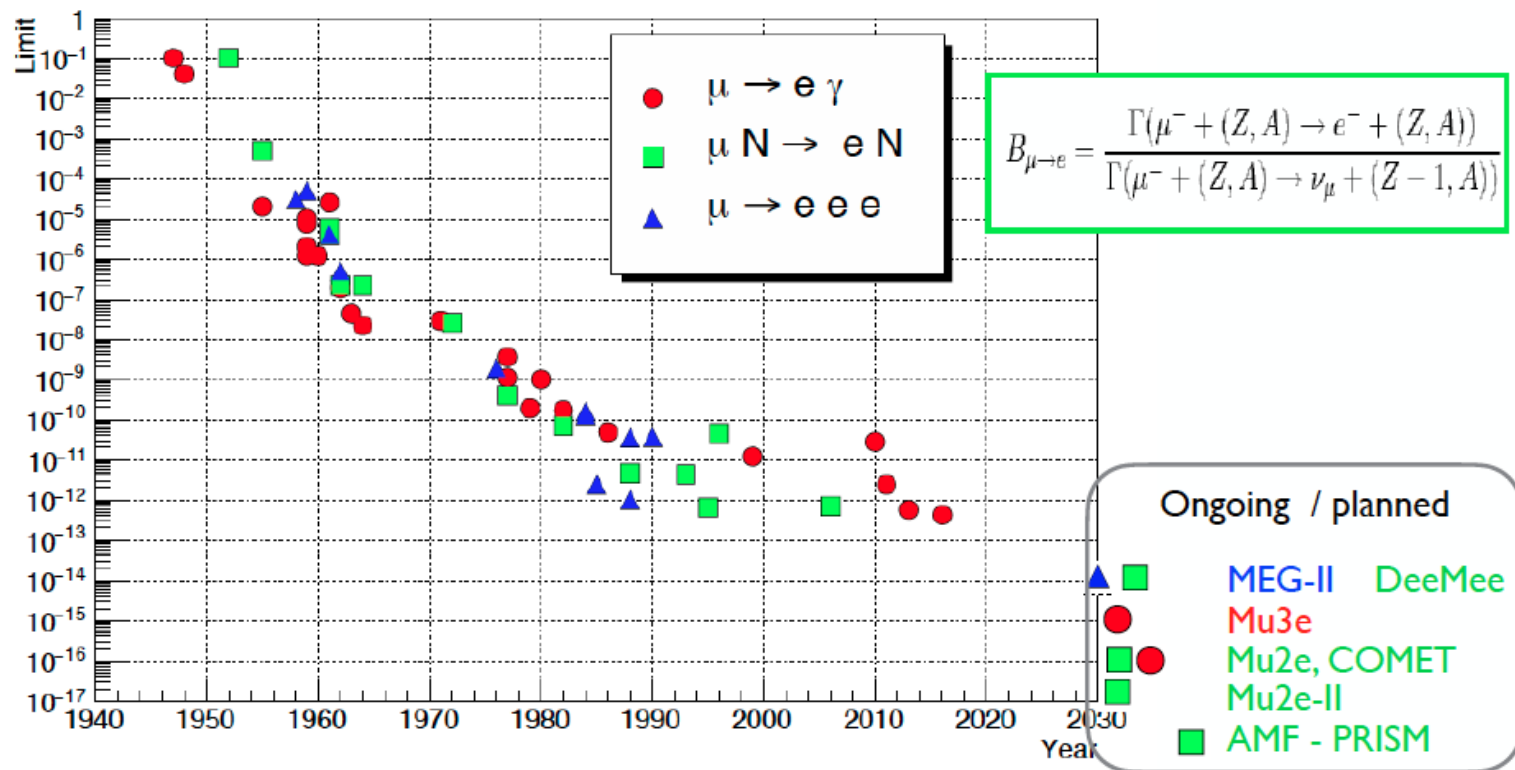
The fact that $\mu \rightarrow e\gamma$ did not happen, led one to postulate that the two neutrino states produced in muon decay were distinct, and that $\mu \rightarrow e\gamma$, and other similar processes, were forbidden due to symmetries.

To this date, these so-called individual lepton-flavor numbers seem to be conserved in the case of charged lepton processes, in spite of many decades of (so far) fruitless searching...

- Decays of μ , τ (and mesons)

$$\mu \rightarrow e\gamma, \quad \mu \rightarrow e\bar{e}e, \quad \mu(A, Z) \rightarrow e(A, Z) \quad M_\mu - \bar{M}_\mu \quad \mu \rightarrow ea$$

$$\tau \rightarrow \ell\gamma, \quad \tau \rightarrow \ell_\alpha \bar{\ell}_\beta \ell_\beta, \quad \tau \rightarrow \ell Y \quad Y = P, S, V, P\bar{P}, \dots$$

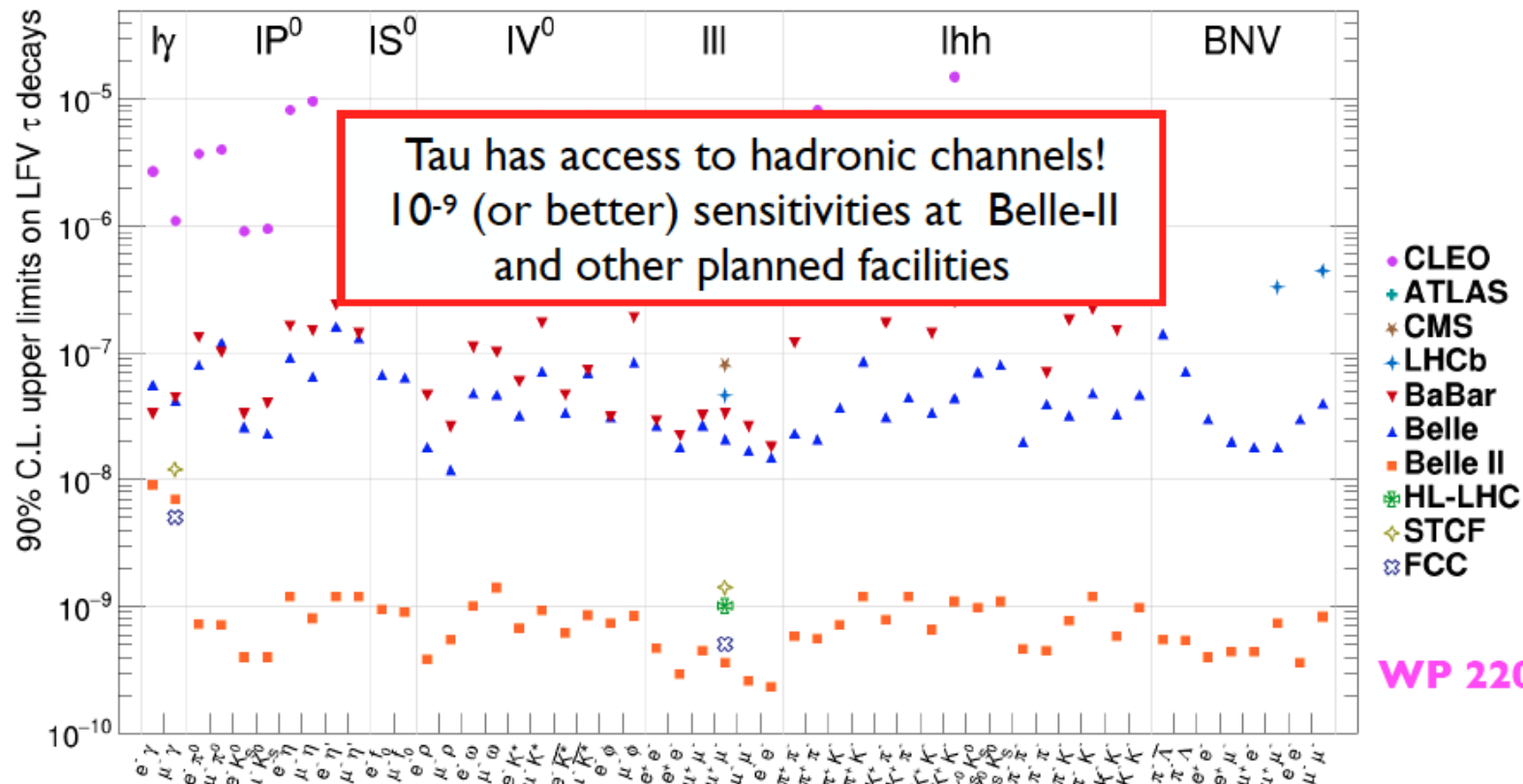


[talk by V. Cirigliano, RP Plenary Session (07/21)]

Decays of μ , τ (and mesons)

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$$\tau \rightarrow \ell\gamma, \quad \tau \rightarrow \ell_\alpha \bar{\ell}_\beta \ell_\beta, \quad \tau \rightarrow \ell Y \quad Y = P, S, V, P\bar{P}, \dots$$



WP 2203.14919

\Rightarrow (also B violation!)

[talk by V. Cirigliano, RP Plenary Session (07/21)]

SM Expectations?

In the old SM, the rate for charged lepton flavor violating processes is trivial to predict. It **vanishes** because **individual lepton-flavor number** is conserved:

- $N_\alpha(\text{in}) = N_\alpha(\text{out})$, for $\alpha = e, \mu, \tau$.

But individual lepton-flavor number are NOT conserved— ν oscillations!

Hence, in the ν SM (the old Standard Model plus operators that lead to neutrino masses) $\mu \rightarrow e\gamma$ is allowed (along with all other charged lepton flavor violating processes).

These are Flavor Changing Neutral Current processes, observed in the quark sector ($b \rightarrow s\gamma$, $K^0 \leftrightarrow \bar{K}^0$, etc).

Unfortunately, we do not know the ν SM expectation for charged lepton flavor violating processes \rightarrow **we don't know the ν SM Lagrangian !**

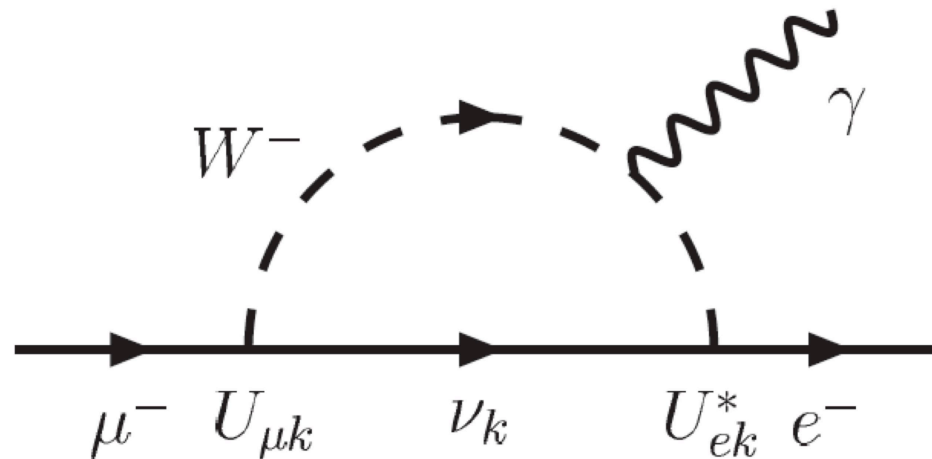
One contribution known to be there: active neutrino loops (same as quark sector).

In the case of charged leptons, the **GIM suppression is very efficient...**

$$\text{e.g.: } Br(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{i1}^2}{M_W^2} \right|^2 < 10^{-54}$$

[$U_{\alpha i}$ are the elements of the leptonic mixing matrix,

$\Delta m_{i1}^2 \equiv m_i^2 - m_1^2$, $i = 2, 3$ are the neutrino mass-squared differences]



Everyone's Favorite Neutrino Mass Model

A simple^a, renormalizable Lagrangian that allows for neutrino masses is

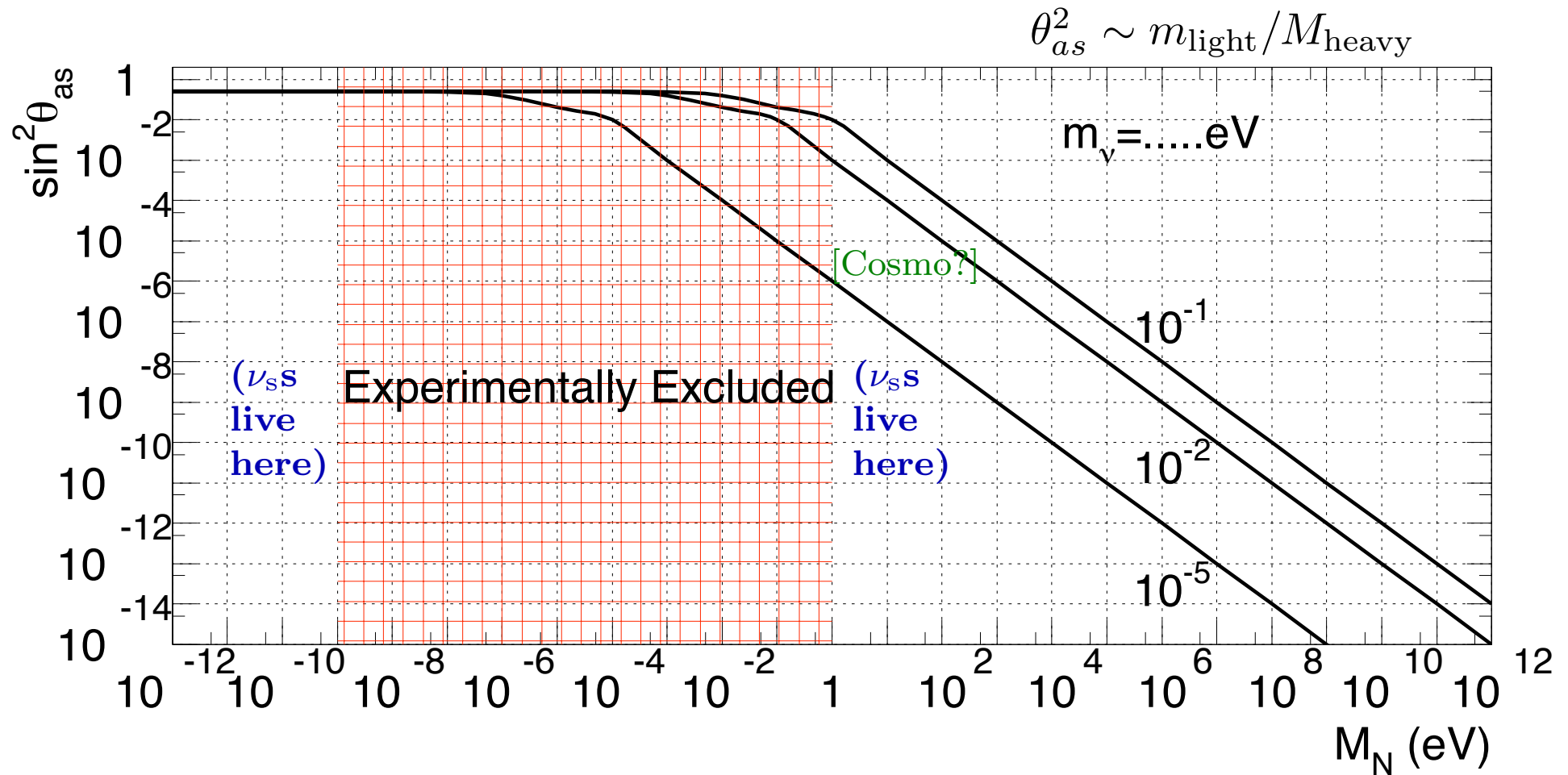
$$\mathcal{L}_\nu = \mathcal{L}_{\text{old}} - \lambda_{\alpha i} L^\alpha H N^i - \sum_{i=1}^3 \frac{M_i}{2} N^i N^i + H.c.,$$

where N_i ($i = 1, 2, 3$, for concreteness) are SM gauge singlet fermions. \mathcal{L}_ν is the most general, renormalizable Lagrangian consistent with the SM gauge group and particle content, plus the addition of the N_i fields.

After electroweak symmetry breaking, \mathcal{L}_ν describes, besides all other SM degrees of freedom, six Majorana fermions: **six neutrinos**.

^aOnly requires the introduction of three fermionic degrees of freedom, no new interactions or symmetries.

Constraining the Seesaw Lagrangian



Theoretical upper bound: $M_N < 7.6 \times 10^{24} \text{ eV} \times \left(\frac{0.1 \text{ eV}}{m_\nu} \right) \Rightarrow \Rightarrow \Rightarrow$

CLFV and Heavy Neutral Leptons

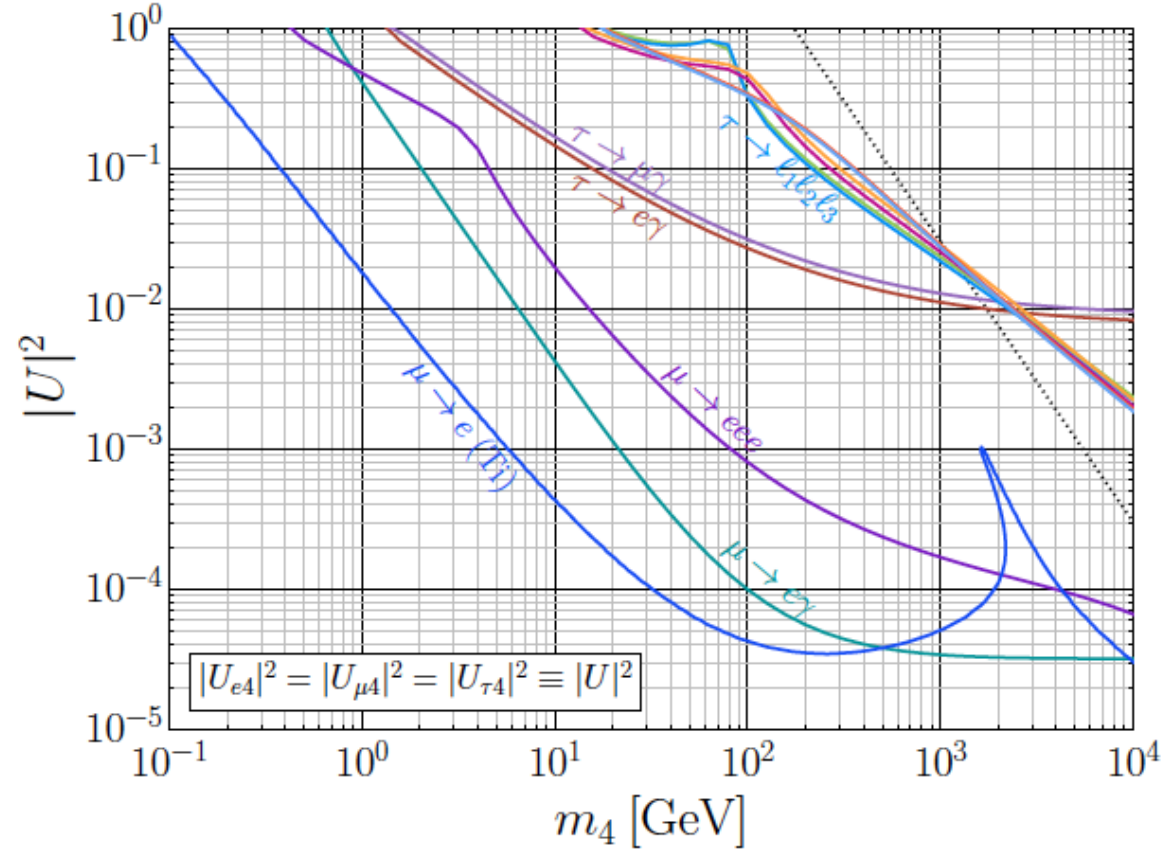


FIG. 2: The 99% CL limit on the neutrino mixing-matrix elements associated with a heavy neutrino, when $|U_{e4}|^2 = |U_{\mu4}|^2 = |U_{\tau4}|^2 \equiv |U|^2$, using experimental constraints on radiative decays, three-body decays [17, 29], and $\mu - e$ conversion on Ti (which gives the strongest constraints of the $\mu - e$ various limits) [17, 27]. The dashed black line corresponds to $|U|^2 = (174 \text{ GeV})^2 / m_4^2$, to the right of which $|U|^2$ values are not expected to be theoretically accessible. See text for details.

AdG, A. Kobach, arXiv:1511.00683

Independent from neutrino masses, there are **strong theoretical reasons** to believe that the expected rate for flavor changing violating processes is much, much larger than naive ν SM predictions and that **discovery is just around the corner**.

Due to the lack of SM “backgrounds,” searches for rare muon processes, including $\mu \rightarrow e\gamma$, $\mu \rightarrow e^+e^-e$ and $\mu + N \rightarrow e + N$ (μ - e -conversion in nuclei) are considered ideal laboratories to probe effects of new physics at or even above the electroweak scale.

Indeed, if there is **new physics at the electroweak scale** (as many theorists will have you believe) and if **mixing in the lepton sector is large “everywhere”** the question we need to address is quite different:

Why haven't we seen charged lepton flavor violation yet?

Model Independent Approach

[see Davidson-Echenard arXiv:2204.00564 for a more modern, thorough discussion!]

As far as charged lepton flavor violating processes are concern, new physics effects can be parameterized via a handful of higher dimensional operators. For example, say that the following effective Lagrangian dominates CLFV phenomena:

$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L)$$

First term: mediates $\mu \rightarrow e\gamma$ and, at order α , $\mu \rightarrow eee$ and $\mu + Z \rightarrow e + Z$

Second term: mediates $\mu + Z \rightarrow e + Z$ and, at one-loop, $\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$

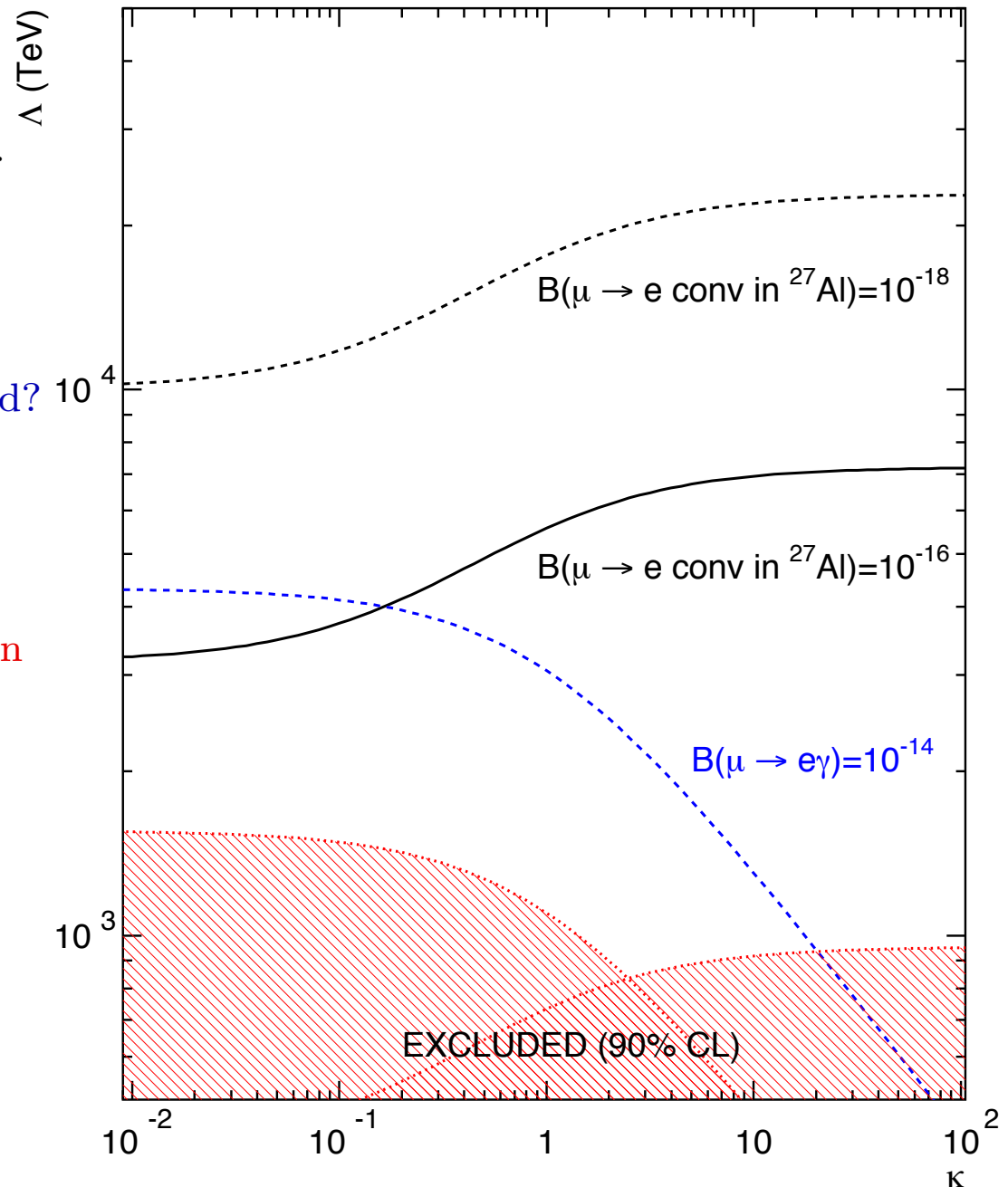
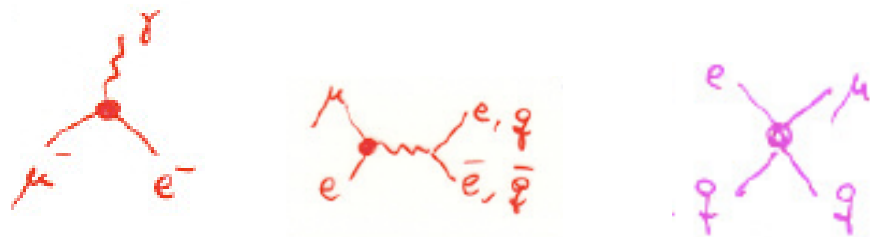
Λ is the “scale of new physics”. κ interpolates between transition dipole moment and four-fermion operators.

Which term wins? \rightarrow Model Dependent

- $\mu \rightarrow e$ -conv at 10^{-17} “guaranteed” deeper probe than $\mu \rightarrow e\gamma$ at 10^{-14} .

- It is really hard to do $\mu \rightarrow e\gamma$ much better than 10^{-14} . $\mu \rightarrow e$ -conv “best” way forward?

- If the LHC does not discover new states $\mu \rightarrow e$ -conv among very few process that can access 10,000+ TeV new physics scale:
tree-level new physics: $\kappa \gg 1$, $\frac{1}{\Lambda^2} \sim \frac{g^2 \theta_{e\mu}}{M_{\text{new}}^2}$.



Other Example: $\mu \rightarrow ee^+e^-$

$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L \bar{e} \gamma^\mu e$$

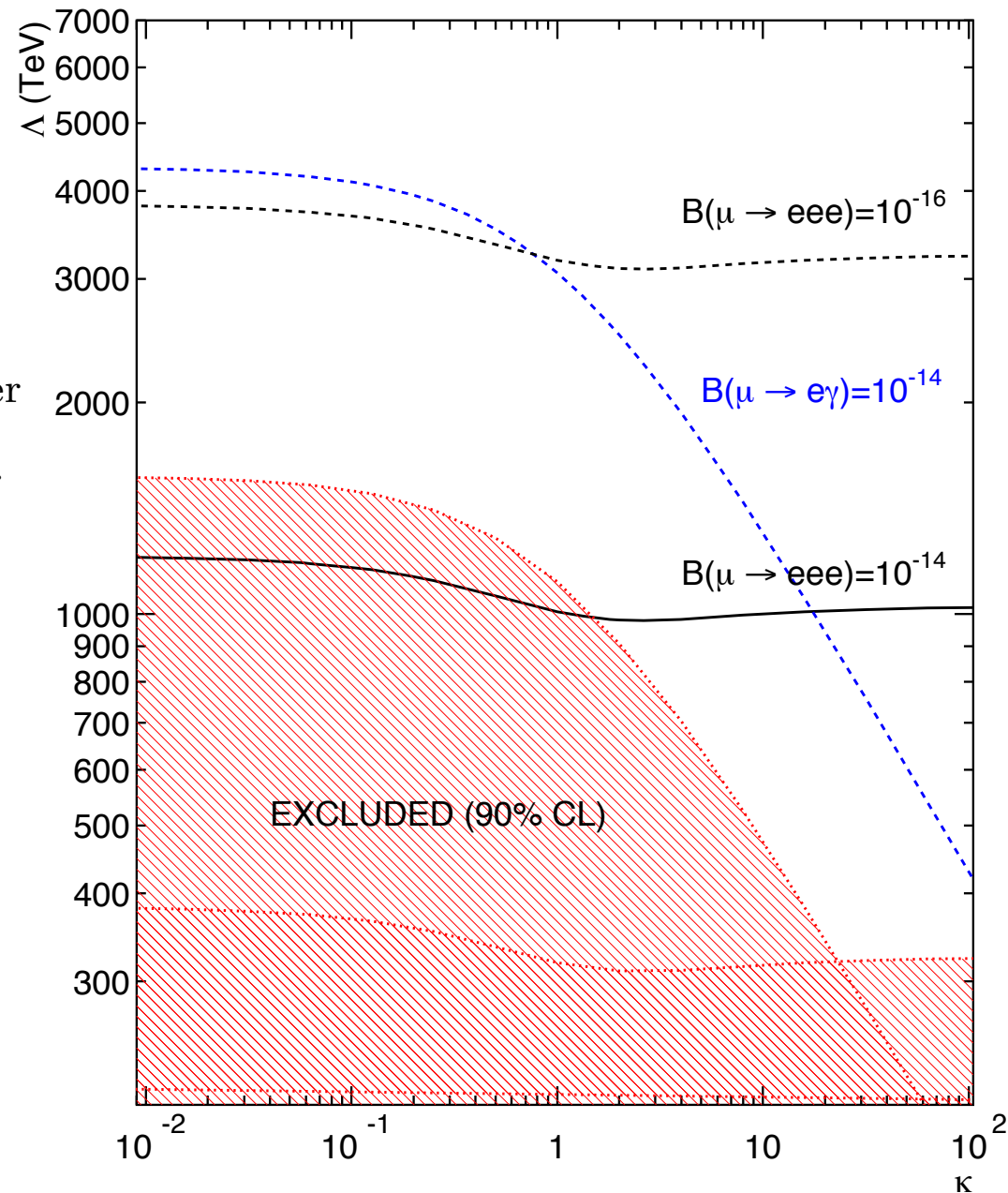
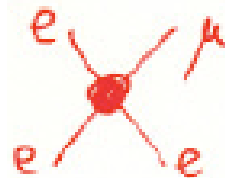
- $\mu \rightarrow eee$ -conv at 10^{-16} “guaranteed” deeper probe than $\mu \rightarrow e\gamma$ at 10^{-14} .

- $\mu \rightarrow eee$ another way forward after MEG?

- If the LHC does not discover new states $\mu \rightarrow eee$ among very few process that can

access 1,000+ TeV new physics scale:

tree-level new physics: $\kappa \gg 1$, $\frac{1}{\Lambda^2} \sim \frac{g^2 \theta_{e\mu}}{M_{\text{new}}^2}$.



What does “ Λ ” mean?

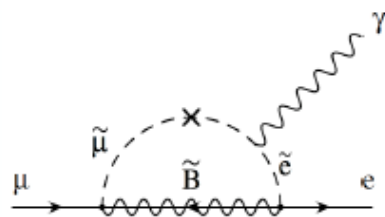
This is clearly model dependent! However, some general issues are easy to identify...

- $\mu \rightarrow e\gamma$ always occurs at the loop level, and is suppressed by E&M coupling e . Also chiral suppression (potential for “ $\tan \beta$ ” enhancement).

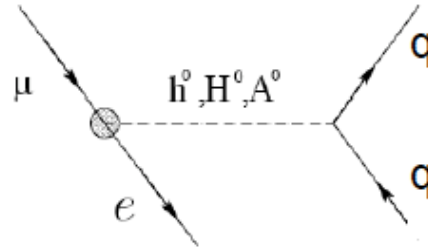
$$\frac{1}{\Lambda^2} \sim \frac{e}{16\pi^2} \frac{\tan \beta}{M_{\text{new}}^2}$$

- $\mu \rightarrow eee$ and $\mu \rightarrow e$ -conversion in nuclei can happen at the tree-level

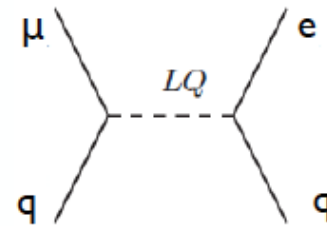
$$\frac{1}{\Lambda^2} \sim \frac{y_{\text{new}}^2}{M_{\text{new}}^2}$$



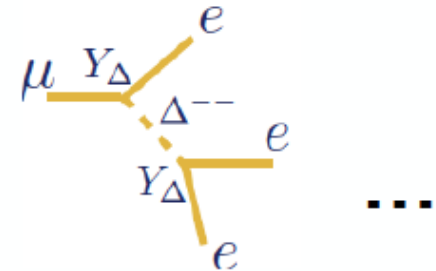
Dipole: SUSY-GUT and
SUSY see-saw scenarios,
...



Scalar: RPV SUSY and RPC
SUSY for large $\tan(\beta)$ and
low m_A , leptoquarks, ...



Vector Type III seesaw,
LRSM, leptoquarks, ...



4-lepton: Type II seesaw,
RPV SUSY, LRSM, ...

$$\mathcal{L}_{d=6} \supset \frac{v C_D^{\alpha\beta}}{\Lambda^2} \bar{\ell}^\alpha \sigma_{\mu\nu} \ell^\beta F^{\mu\nu} + \sum_{\Gamma} \frac{C_{\Gamma}^{\alpha\beta}}{\Lambda^2} \bar{\ell}^\alpha \Gamma \ell^\beta \bar{q} \Gamma q + \sum_{\tilde{\Gamma}} \frac{C_{\tilde{\Gamma}}^{\alpha\beta}}{\Lambda^2} \bar{\ell}^\alpha \tilde{\Gamma} \ell^\beta \bar{\ell} \tilde{\Gamma} \ell$$

(Will not discuss the interesting case of ALPs with LFV couplings, see Calibbi et al. 2006.04795)

[talk by V. Cirigliano, RP Plenary Session (07/21)]

Type-II Seesaw: SM plus $SU(2)$ Triplet Higgs, $Y_T = 1$

$$\mathcal{L} \in \frac{\lambda_{\alpha\beta}}{2} L^\alpha L^\beta T.$$

Neutrino Majorana masses if T develops a vev ...

$$m_{\alpha\beta} = \lambda_{\alpha\beta} v_T$$

$\mu \rightarrow e\gamma$, $\mu \rightarrow e$ -conversion at the loop-level. However, $\mu \rightarrow eee$ at the tree level (note direct connection to neutrino mass-matrix flavor structure)...

$$\frac{1}{\Lambda^2} = \frac{m_{ee} m_{\mu e}}{v_T^2 M_T^2}$$

Key issue: are neutrino masses small because λ are small or because v_T is small (or both)? EWPD already push v_T below ~ 1 GeV...

What is This Really Good For?

While specific models provide estimates for the rates for CLFV processes, the observation of one specific CLFV process cannot determine the underlying physics mechanism (this is always true when all you measure is the coefficient of an effective operator).

Real strength lies in combinations of different measurements, including:

- kinematical observables (e.g. angular distributions in $\mu \rightarrow eee$);
- other CLFV channels;
- neutrino oscillations;
- measurements of $g - 2$ and EDMs;
- collider searches for new, heavy states;
- etc.

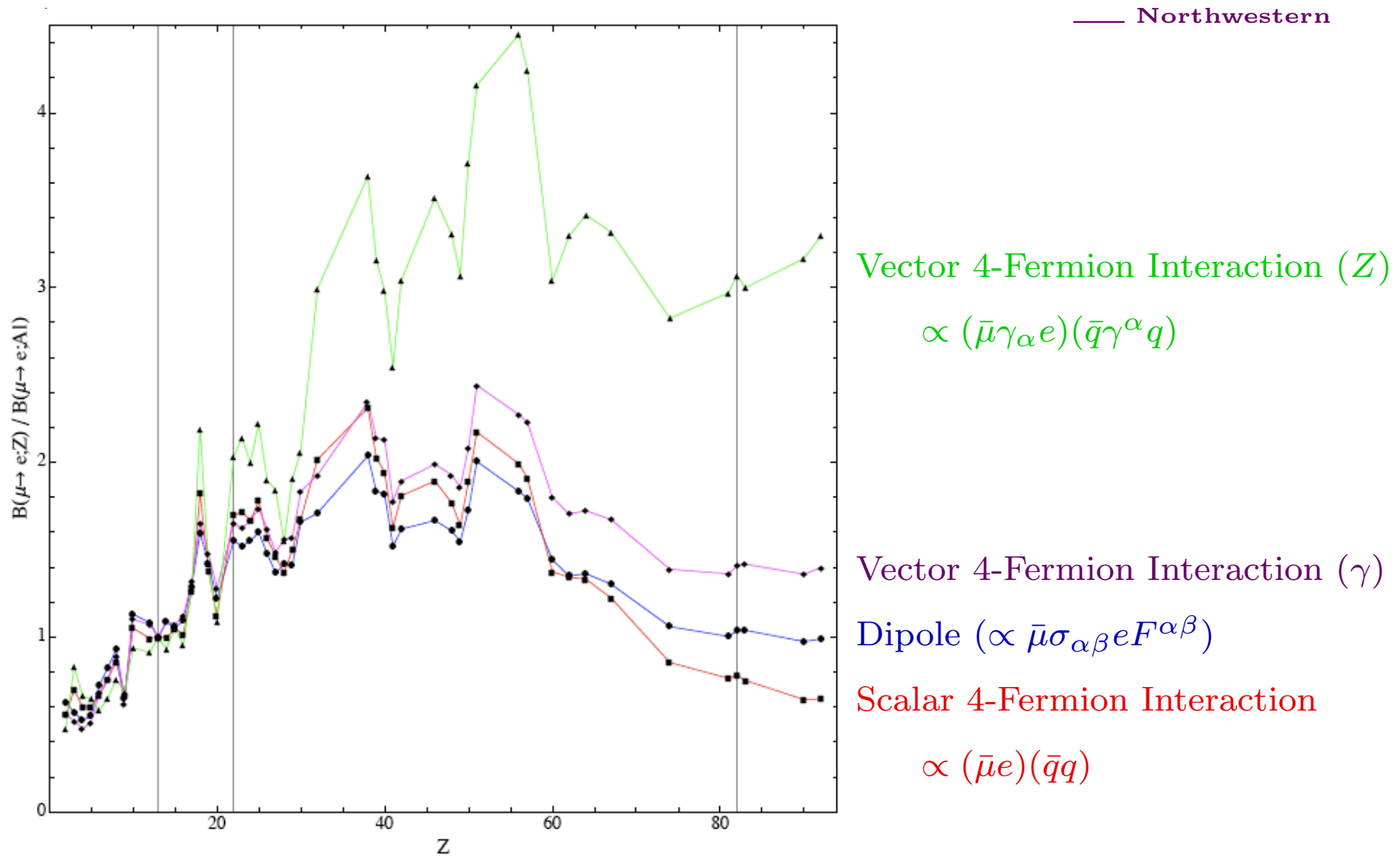


Figure 3: Target dependence of the $\mu \rightarrow e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ($Z = 13$) versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$ (magenta), $V^{(Z)}$ (green). The vertical lines correspond to $Z = 13$ (Al), $Z = 22$ (Ti), and $Z = 83$ (Pb).

Model Independent Comparison Between $g - 2$ and CLFV:

The dipole effective operators that mediate $\mu \rightarrow e\gamma$ and contribute to a_μ are virtually the same:

$$\frac{m_\mu}{\Lambda^2} \bar{\mu} \sigma^{\mu\nu} \mu F_{\mu\nu} \quad \times \quad \theta_{e\mu} \frac{m_\mu}{\Lambda^2} \bar{\mu} \sigma^{\mu\nu} e F_{\mu\nu}$$

$\theta_{e\mu}$ measures how much flavor is violated. $\theta_{e\mu} = 1$ in a flavor indifferent theory, $\theta_{e\mu} = 0$ in a theory where individual lepton flavor number is exactly conserved.

If $\theta_{e\mu} \sim 1$, $\mu \rightarrow e\gamma$ is a much more stringent probe of Λ .

On the other hand, if the current discrepancy in a_μ is due to new physics,

$\theta_{e\mu} \ll 1$ ($\theta_{e\mu} < 10^{-4}$). [Hisano, Tobe, hep-ph/0102315]

e.g., in SUSY models, $Br(\mu \rightarrow e\gamma) \simeq 3 \times 10^{-5} \left(\frac{10^{-9}}{\delta a_\mu} \right) \left(\frac{\Delta m_{\tilde{e}\tilde{\mu}}^2}{\tilde{m}^2} \right)^2$

Comparison restricted to dipole operator. If four-fermion operators are relevant, they will “only” enhance rate for CLFV with respect to expectations from $g - 2$.

Very quick comments on the muon electric-dipole moment, d_μ

- CP-violating observable;
- Predicted to be non-zero-but-tiny in the SM: $d_\mu < 10^{-36}$ e-cm. Great place to look for new physics!
- Current bounds: $d_\mu < 1.8 \times 10^{-19}$ e-cm. Compare to $d_e < 10^{-27}$ e-cm.
- In general, $d_\ell \propto m_\ell$, so $d_\mu \sim d_e \times (m_\mu/m_e)$.
- New $g - 2$ experiment at FNAL would be sensitive to $d_\mu > 10^{-21}$ e-cm. Dedicated effort could reach $d_\mu > 10^{-24}$ e-cm. Is it worth it? [yes!]
- Same effective operator contributes to a_μ and d_μ

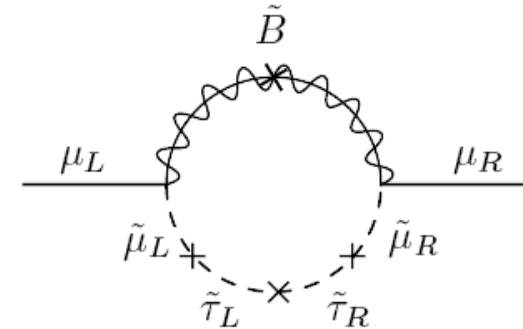
$$\frac{m_\mu}{\Lambda^2} \bar{\mu} \sigma_{\mu\nu} \mu F^{\mu\nu} \quad \text{versus} \quad \epsilon_{\text{CP}} \frac{m_\mu}{\Lambda^2} \bar{\mu} \sigma_{\mu\nu} \gamma_5 \mu F^{\mu\nu}.$$

ϵ_{CP} measures how much the new physics violates CP.

[see 1008.5091 and hep-ph/0108275]

[T. Rüppell, talk at PSI]

- Only $\tilde{\tau}$ - $\tilde{\mu}$ mixing.
- Only $m_\tau \neq 0$.
- Chirality flipping $A_{E_{23}} = A_{E_{32}} = 0$.
- Leading contribution from Bino loop.



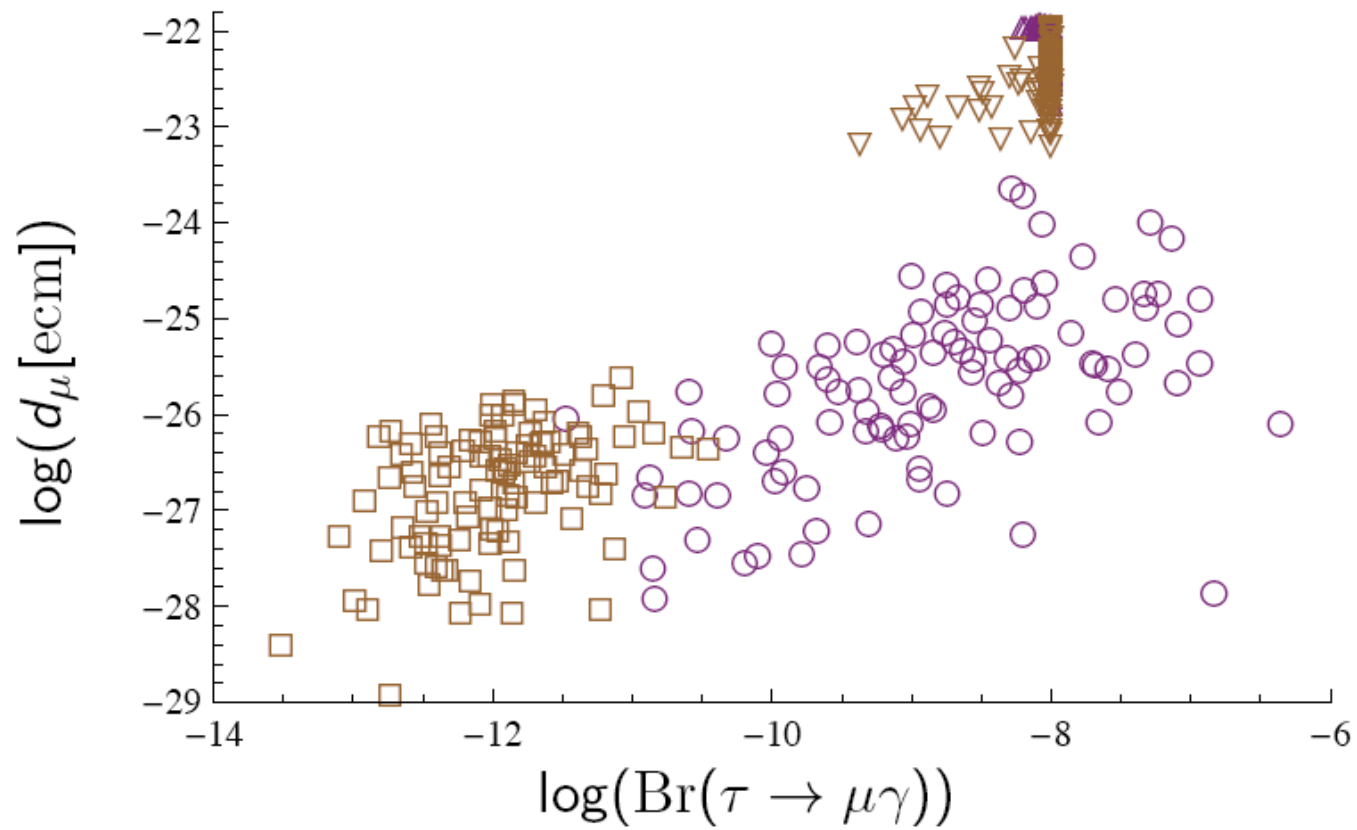
$$\frac{d_\mu}{e} = \frac{\alpha}{2\pi} \frac{M_i}{M_{\tilde{A}}^2} G_1\left(\frac{M_i^2}{M_{\tilde{A}}^2}\right) \text{Im}(\delta_{22}^{L_L E}) \sim 1 \cdot 10^{-20} \text{cm} \left(\frac{200 \text{GeV}}{M_{\tilde{A}}}\right) \text{Im}(\delta_{23}^{L_L} \delta_{33}^{L_L E} \delta_{23}^{E*}).$$

- We assume maximal CP violating phases in $\delta_{23}^{L_L} \delta_{23}^{E*}$.
- Fixing the stau left-right mixing $\delta_{33}^{L_L E}$ connects $A_{E,33}$, μ , $\tan \beta$ and $M_{\tilde{A}}$.
- The MIA calculation for $\text{Br}(\tau \rightarrow \mu \gamma)$ gives

$$\text{Br}(\tau \rightarrow \mu \gamma) = \kappa(|\delta_{23}^{L_L}|^2 + |\delta_{23}^E|^2), \quad \max |\delta_{23}^{L_L} \delta_{23}^E| = \text{Br}(\tau \rightarrow \mu \gamma)_{\text{max}} / (2\kappa).$$

$$\kappa = \left(1 + \frac{M_i}{m_\tau} \frac{G_1(y)}{G_3(y)} \delta_{33}^{L_L E}\right)^2 \frac{\alpha^3}{G_F^2} \frac{12\pi}{M_{\tilde{A}}^4} G_3(y)^2 \times \mathcal{B}(\tau \rightarrow \mu \nu \bar{\nu}), \quad y = \frac{M_i^2}{M_{\tilde{A}}^2}.$$

[T. Rüppell, talk at PSI]



On CLFV Processes Involving τ Leptons (Brief Comment)

Current Bound On Selected τ CLFV Processes (All from the B -Factories):

- $B(\tau \rightarrow e\gamma) < 1.1 \times 10^{-7}$; $B(\tau \rightarrow \mu\gamma) < 4.5 \times 10^{-8}$. $(\mu \rightarrow e\gamma)$
- $B(\tau \rightarrow e\pi) < 8.0 \times 10^{-8}$; $B(\tau \rightarrow \mu\pi) < 1.1 \times 10^{-7}$. $(\mu \rightarrow e\text{-conversion})$
- $B(\tau \rightarrow eee) < 3.6 \times 10^{-8}$; $B(\tau \rightarrow ee\mu) < 2.0 \times 10^{-8}$, $(\mu \rightarrow eee)$
- $B(\tau \rightarrow e\mu\mu) < 2.3 \times 10^{-8}$; $B(\tau \rightarrow \mu\mu\mu) < 3.2 \times 10^{-8}$. $(\mu \rightarrow eee)$

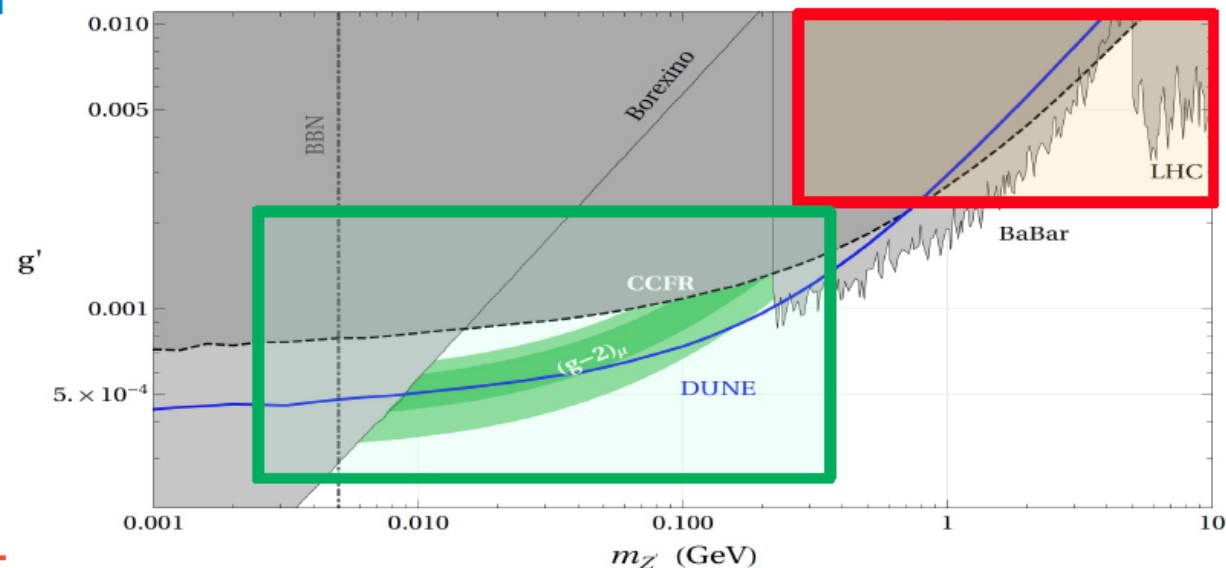
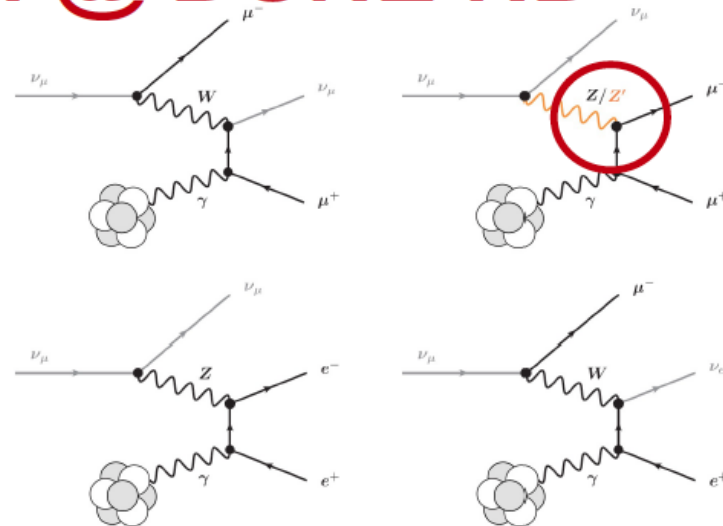
Relation to $\mu \rightarrow e$ violating processes is model dependent. Typical enhancements, at the amplitude-level, include:

- Chirality flipping: $m_\tau \gg m_\mu$;
- Lepton mixing effects: $U_{\tau 3} \gg U_{e3}$;
- Mass-Squared Difference effects: $\Delta m_{13}^2 \gg \Delta m_{12}^2$;
- etc

Ask not only what muons can do for neutrinos but what neutrinos can do for muons ...

ν -Trident Search @ DUNE ND

- SM predicts the neutrino tridents through rare weak processes \rightarrow produces a pair of charged leptons.
- **Unknown gauge boson couplings** could cause deviations in the SM predicted signal yields
- DUNE sensitive in the region where $(g-2)_\mu$ anomaly can be explained at the 1σ and 2σ level



Summary and Conclusions

- Low-energy muon processes constitute a powerful (often unique) probe of new physics around the electroweak scale, not unlike high-energy collider experiments (similar sensitivity to new physics energy scale).
- We know that charged lepton flavor violation must occur. Effects are, however, really tiny in the “minimal” ν SM (neutrino masses too small).
- If there is new physics at the electroweak scale, there is every reason to believe that CLFV is well within the reach of next generation experiments. Indeed, it is fair to ask: ‘Why haven’t we seen it yet?’
- It is fundamental to probe all CLFV channels. While in many scenarios $\mu \rightarrow e\gamma$ is the “largest” channel, there is no theorem that guarantees this (and many exceptions).
- CLFV may be intimately related to new physics unveiled with the discovery of non-zero neutrino masses. It may play a fundamental role in our understanding of the seesaw mechanism, GUTs, the baryon-antibaryon asymmetry of the Universe. We won’t know for sure until we see it!